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# Cosmic Rays, Solar Activity, Magnetic Coupling, and Lightning Incidence

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# **Cosmic Rays, Solar Activity, Magnetic Coupling, and Lightning Incidence**

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## INTRODUCTION

MANY THEORIES have been advanced for each of the various aspects of thunderstorm phenomenology. Arguments have been offered both in support and in criticism of essentially all of these theories as part of the process of model evolution. Similarly, this paper describes a theoretical model and then tests its predictions against the data by showing they form a consistent set of explanations for a number of major findings previously unexplained, misinterpreted or thought to be conflicting. In view of (1) the importance of the atmospheric-electricity/solar-terrestrial research areas, (2) the limitations on funds, and (3) the cost of investigating erroneous concepts, theoretical differences must be resolved as early as possible in the program.

Lightning incidence or frequency exhibits great variation in time and space. Spatial or global lightning patterns can be seen in plots made from satellite data [1, 2, 3] and, on a different scale, in photographs made from orbit [4]. Temporal patterns of lightning incidence can be made by time records of any variable correlated with local or with global lightning such as sferics or atmospheric electrical potential gradient [5]. Many factors are involved in shaping these patterns. The standard meteorological variables including moisture content, temperature distributions, orographic lift, etc., are generally understood, at least in broad principle. However, even in these long studied areas of storm physics, establishment of details for many features, such as charge separation and transport, are still hindered by the complexity and experimental difficulties arising from the number of variables and the range of scales involved ( $10^{-10}$  to greater than  $10^4$  m). A less studied and less "obvious" but major determinant of lightning patterns is the distribution of ionization from somewhat below 10 km to approximately 50 km (a level called the "electrosphere"). This factor, related to the atmospheric electrical conductivity, and the processes that perturb it are the topics of interest to this paper.

In essence, the theory to be developed will show that solar activity should strongly influence lightning frequency by several processes that markedly modulate the atmospheric conductivity above thunderstorms and hence the fraction of the thunderstorm's upward (positive) current that leaks away to the electrosphere. Among the several processes are: (1) the modulation of galactic cosmic ray intensity over the 11-year solar sunspot cycle with the maxima in cosmic rays occurring at the sunspot minima, (2) Forbush decreases in cosmic ray intensity due to "magnetized clouds" of solar plasma enveloping the earth for several days and occurring most often near the solar cycle maxima, and (3) magnetic coupling, an essentially weekly process to be discussed at length. As one example of these processes, high cosmic ray ionization above a thundercloud, common near the sunspot cycle minimum,

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### Abbreviations Used:

C9	= geomagnetic activity index
EqM	= equatorial modulation
GMF	= geomagnetic field
IMF	= interplanetary magnetic field
Kp	= a geomagnetic activity index
N	= negative;
	P = positive
NM	= neutron monitor
NSA	= north-south asymmetry

greatly increases the storm's leakage current and therefore also increases the time required for the small remaining current to charge the cloud to striking potential. This is predicted to result in less lightning and, under certain conditions, a higher electrosphere potential during that part of the solar cycle or at any time such increases in conductivity occur. Other aspects of the model suggest: (1) altered 10 km ionization also has a major influence on weather and climate via cirrus with the effect expected to be stronger at high geomagnetic latitude, but (2) any changes in the potential do not have significant (first order) effects on either thunderstorms or climate. Hence, the model suggests upper troposphere and tropopause ionization is a much more important quantity than the more difficult to measure electrospheric potential. Thus, although the ultimate cause of variation in this upper air conductivity is solar activity, the causal chain involves a number of additional factors including atmospheric electricity, cosmic radiation, the solar cycle and two forms of magnetic coupling (one form of which is called "connection" or "merging") between the geomagnetic field (GMF) and the interplanetary magnetic field (IMF). The "connection" model has organized many observations and has made a number of predictions later confirmed experimentally [6, 7]. Before the theory is applied to interpretation of the data, a review of certain relevant aspects of these several factors will be given.

## DISCUSSION

ATMOSPHERIC ELECTRICITY--It has long been known that ionization of the atmosphere in the altitude region from about a kilometer up to the electrosphere is almost entirely due to the cosmic radiation. The atmosphere can be considered the (leaky) dielectric between the two spherical capacitor shells formed by the earth's surface and the electrosphere in this simplified model. From the downward direction and the sea level value of approximately 100 volts per meter for the fair-weather atmospheric vertical electrostatic field ( $E$ ), one calculates a negative charge of 450,000 coulombs resides on the earth's surface. Above the electrosphere,  $E$  is everywhere very small or zero. Thus, an equal positive shell of 450,000 coulombs must exist between sea level and 50 km. If all of this positive charge were located at 50 km (i.e. on the surface of the electrosphere),  $E$  would still be nearly 100 volts per meter just below that surface. However, it is found that  $E$  has decreased to approximately 5 volts per meter at only 10 km. (The potential of the electrosphere with respect to the ground as zero is found by a line integral of  $E$  from the surface up to 50 km. It has a value that varies between about 220 and 350 KV with time of day and of year [5] and of the solar cycle.) Thus, a positive space charge of about 430,000 coulombs (i.e. 95% of the sea level surface charge) must exist in the 10 km thick atmospheric shell just above the earth's surface. Other measurements show that a positive air-earth current flows downward, is fairly constant throughout the altitude interval of interest, and is estimated to be approximately 1500 amperes for the entire earth (a few picoamperes per square meter). This current would essentially discharge the earth-electrosphere capacitor in 10 minutes if no countercurrent existed. The equilibrium is believed to be maintained by an opposite (upward flowing) positive current of 1500 amperes provided by about 1/2 ampere average from each of the earth's approximately 3000 thunderstorms.

Associated with a given thundercloud and other matter affected by its field, a number of different charge separation and transport processes exist [8, 9, 5]. Charges of both signs are liberated and transported in all directions by precipitation, convection, lightning, etc. The overall result is a positive



current upward composed of both a net downward transport of negative and a net upward transport of positive charge. The upward flowing positive charge in effect divides and contributes both to charging of the upper positive (P) region and to leakage out the sides and top of the cloud along the electrostatic field lines due mainly to the dipole of the cloud and its image in the earth below. It should be noted that charge leaking upward from the top of the cloud to the electrosphere is, of course, actually falling down the potential gradient because the cloud top potential is between  $10^8$  and  $10^9$  volts above ground while the electrosphere is only approximately  $3 \times 10^5$  volts. Thus, we see the 1/2 ampere (approximate) current measured above single thunderstorms indicates the effective resistance above one storm, between it and the electrosphere, is about  $10^9$  ohms ( $R_u$ ). Also, the effective total resistance therefore between all 3000 thunderstorm generators (in parallel) and the electrosphere is of the order of  $10^6$  ohms. However, the 300,000 volt electrosphere potential driving a 1500 ampere leakage current through the atmosphere to earth indicates the total resistance between the electrosphere and the ground is only 200 ohms. A complete description of an equivalent circuit for even one storm would involve many components, primarily resistors and capacitors. The general scheme has been well represented in the literature [10, 11, 5]. The concern here need only focus upon two variables, the changes in  $R_u$  and the resulting division of the storm's upward flowing current into the charging and leakage components. Notice  $R_u$  is determined by the ionization between about 10 km and the electrosphere which commonly varies coherently with the more easily measured ionization at the 10 km level itself. For this and other reasons, it is often convenient simply to refer to changes in the 10 km ionization. As mentioned earlier, increases in the cosmic ray or other ionization of the region above the storm decreases  $R_u$  increasing the current leaking from the cloud top to the electrosphere and decreasing that left to charge up the cloud's P region. Two interesting effects result from these changes: (1) the electrosphere potential may be raised by the increased current leaking to it from the top of the affected thunderstorm(s) if not simultaneously canceled by other oppositely affected storms, and (2) lightning frequency is reduced because the smaller charging currents require a longer time to reach striking potentials. To compare the relative magnitudes of these two effects, a halving of  $R_u$  above a single storm would add only one part in 3000 to the electrosphere charging current but might decrease the storm's charging current by 50% or so. One of the second order effects possible may be the increased probability of striking from the storm's N region if only the (upper) P region is weakened by the increased leakage current. In a typical case of interest to us, a large region at high latitude possibly involving 5 or 10% of the earth's thunderstorms may have charging rates altered. It was shown by E. P. Ney that atmospheric ionization above thunderstorms at, say, 30 km altitude can change by nearly 60% over a solar cycle [12]. Similar changes of order one-half are induced by other variations in cosmic rays that will be discussed. Ney also recognized that these changes might have relevance to the weather. A theory of weather influence via high latitude cirrus effects has been based on these alterations of high altitude ionization [13]. The theory being presented in this paper is also based on the same findings. A later section will show that observations of lightning incidence vary over the solar cycle by an amount to be expected on the basis of the above discussion.

**COSMIC RADIATION**--The galactic cosmic radiation consists of approximately 90% protons and 9% alphas (helium nuclei) and 1% nuclei with  $Z$  greater than 2. This flux has a spectrum exhibiting a broad peak from approximately 300 to 1000 Mev (i.e. 1 Gev) per nucleon and a long power law tail decreasing as approximately the third power of the energy. Two components of the galactic cosmic ray spectrum are of

principal interest to this paper: the extremely variable low energy peak that contains most of the particles, and the fairly constant high energy tail. The high energy tail beyond about 10 GeV has access to, and produces atmospheric ionization at, essentially all altitudes and latitudes of the earth. The high energy flux changes very little over the solar cycle (but does exhibit a low latitude magnetic coupling effect quite different from that of the low energy flux). On the other hand, the low energy flux (below about 2 GeV per nucleon) only reaches the upper part of the atmosphere and only at high latitudes because of the geomagnetic field (GMF). For example, a 1 GeV proton can only penetrate down to approximately the 10 km altitude. Hence, the broad and variable peak is the dominant factor in determining ionization above high latitude thunderstorms and their value of  $R_{\text{U}}$ . These numerous cosmic ray protons that occupy the energy spectrum peak near 1 GeV have the following characteristics of relevance here: (1) as stated above, they stop at approximately 10 km; (2) they only enter the earth's atmosphere at geomagnetic latitudes above about  $60^\circ$ ; (3) they are strongly modulated (i.e. approximately 60%) by the solar wind changes over the solar cycle; and (4) they are essentially excluded from high latitude regions during magnetic connection of those regions to the sun. The reason for this strong effect on the 1 GeV proton flux by magnetic coupling is that the radius of curvature of such particles at approximately 10 earth radii above the magnetic poles is also equal to 10 earth radii which is also approximately the curvature change of the GMF in those regions during connection to the IMF. This is called resonant scattering. Much lower energy protons would spiral along the field lines and find their way in in spite of morphological alterations in the GMF. Much higher energy protons would still penetrate unimpeded by such merging of the fields. Thus, the "low energy" component of the cosmic radiation permits changes in solar activity to alter upper air ionization and hence lightning frequency.

**THE SOLAR CYCLE AND MAGNETIC COUPLING**--The solar wind consists of an essentially collisionless plasma of ionized hydrogen (protons and electrons) that sweeps out from the sun past the earth at speeds of perhaps 300 km per second during solar minimum and 600 km per second at solar maximum. Because this low density plasma is collisionless it acts as a superconductor and transports the sun's photospheric magnetic field outward from its surface, dragging it along in the plane of the ecliptic. This magnetic burden of the solar wind, the IMF, commonly points approximately away from or toward the sun. Depending upon the region of origin on the solar surface, the field transported from the sun can have different polarities, outward called positive, and inward called negative. The resulting pattern of alternating positive and negative polarity IMF regions tends to repeat itself each 27 days at the earth due to solar rotation. The alternation of IMF polarities induces two different local modulations at earth in the galactic cosmic radiation by two magnetic coupling processes. One strongly affects the low energy (about 1 GeV) flux at high geomagnetic latitudes by a process called merging or connection inducing a north-south asymmetry (NSA) in the flux. The other process produces an equatorial modulation (EqM) in the high energy (above about 5 GeV) flux reaching the atmosphere at low latitudes [14, 6].

**Connection and the NSA (Description)**--When the earth is in a positive sector, IMF pointing away from the sun and toward the earth, the configuration is correct for connection by an IMF flux tube to the north pole region of the GMF where flux enters the earth. In negative sectors, the topology is correct for connection only at the south pole. Connection of the IMF and GMF is analogous to that between two simple dipole magnets that connect (and attract each other) when their orientation is antiparallel (opposite) but repel, i.e. do not connect, when

parallel. Similarly, for (local) cancellation, merging and connection to take place, a flux tube or **bundle** of the IMF must point **approximately** opposite to the GMF where they are pressed together by the solar wind on the "bow" side of the earth in the GMF's equatorial plane. **Because** the GMF always points north at  $0^\circ$  latitude, a southward component of the IMF is required. Because of the several day solar wind radial transit time and because of rotational effects in the earth-sun system, the IMF arrives at earth with an azimuth approximately  $45^\circ$  west of the earth-sun line. Although the average direction of the IMF is along this spiral line ("toward" or "away" from the sun), instantaneous directions can vary greatly due to turbulence, etc., and, of course, during collision with the GMF. When an IMF southward flux tube cancels an equal amount of GMF flux in the bow side merging region, those flux tubes link, connecting one GMF pole to the sun.

The probability of merging appears to be greatest when the GMF direction is closest to that of the IMF, requiring less bending. When a southward IMF occurs, the oppositely directed GMF and IMF fluxes cancel in the bow side equatorial merging region, and the parent IMF flux lines entering the region from the north link or connect to the parent GMF lines also entering from the north, as stated above. This, of course, connects the sun to the earth's north magnetic pole **if** the IMF sector is positive. Because the sun is a very poor source of 1 Gev protons, and because of the "resonant scattering" of galactic cosmic ray protons in this approximate energy range by the connected flux tube, the cosmic ray intensity and upper atmospheric ionization generally decrease in northern latitudes. In a similar fashion, connection can occur between the south GMF pole and the sun in a negative IMF sector decreasing cosmic ray upper air ionization at southern latitudes. When a GMF pole is connected to the sun, the arriving 1 Gev cosmic ray flux exhibits a decrease of about 30% in the region of that pole (the flux changes are actually largest at the cusps). An increase in flux occurs at the opposite unconnected pole (which has "opened" out to the galaxy) but appeared in the satellite and neutron monitor (NM) data to be somewhat smaller in magnitude, possibly due to mirroring of the arriving particles. The decrease at one pole and increase at the other are called a north-south asymmetry, occur in the low energy flux, exhibit a strong geomagnetic latitude dependence (peaking near the day side cusps at approximately  $75^\circ$  N and  $75^\circ$  S) and are not to be confused with a much studied but much smaller asymmetry that occurs in many times higher energy cosmic rays measured with respect to ecliptic north and south. The NSA amplitude is large for low energy particles (and vice versa) and may decrease from solar minimum to solar maximum [14, 6].

Parallel/Antiparallel and the EqM (Description)--It was surprising to find a significant modulation in the cosmic rays reaching the atmosphere at low geomagnetic latitudes because of their high energy (approximately 16 Gev threshold for protons arriving along the local vertical) and small change in intensity over the solar cycle. The modulation may have importance both to weather via the cirrus mechanism [13] and to lightning via ionization changes. In the small amount of satellite and NM data analyzed to date, the amplitude of EqM was found to average 30% in the 6 Gev protons arriving horizontally at the top of the atmosphere from the west but appeared to be only 1 to 2% in the Chacaltaya and Haleakala NM data for 1966 to 1968 [6]. The changes in tropopause ionization should be closer to the satellite value of EqM than to the NM values because of the lower threshold (6 Gev) of the flux sampled in orbit. Additional low latitude NM data are now being analyzed, but satellite (or balloon) measurements of low latitude cosmic rays in both positive and negative IMF sectors from solar minimum to solar maximum are needed. In the NM data, EqM weakened approaching the 1964 solar minimum [6]. More data will be analyzed. The mechanism of EqM is extremely simple and is explained in reference 6.

In essence, when the IMF near the earth is approximately parallel to the equatorial GMF (*i.e.* north), the cut-off rigidity is increased and the arriving flux is reduced. Conversely, the flux increases when the IMF and equatorial GMF are antiparallel. The EqM and NSA peak under different conditions and times of the year and of the solar cycle. Usually NSA will have the same sign as EqM at one pole and be opposite at the other. The various factors that determine when they peak and are additive include the  $23.5^\circ$  tilt of the earth's spin axis with respect to ecliptic north, the  $12^\circ$  tilt of the GMF dipole with respect to the spin axis, the  $7.25^\circ$  tilt of the sun's spin axis with respect to ecliptic north, and a warping of the sun's equatorial plane current sheet involved in the Rosenberg-Coleman effect.

**NSA and EqM: Seasonal, Solar Cycle and Latitude Effects--**The questions of relative amplitudes and phases of the ionization perturbations due to the two principal magnetic coupling mechanisms (producing NSA and EqM) are discussed in this section. These considerations (1) determine how the effects add and subtract and (2) are of interest to changes in both lightning intensity and electrospheric potential. The relative orientation of IMF and GMF is, of course, the ultimate variable. The dominant controlling factors are: (1) the sun's magnetic field polarity and amplitude; (2) the directions of the spin axes of sun and earth with respect to both the ecliptic plane and the earth-sun line (or to the IMF spiral direction); (3) the solar wind speed; and (4) warping of the solar equatorial current sheet. The direction variables will be considered first, followed by the solar magnetic dipole polarity, current sheet warping (the Rosenberg-Coleman effect), then wind speed and, finally, a comment on latitude effects.

As discussed above, the solar wind presses the IMF against the bow side of the GMF where the two fields can have relative orientations that range through  $360^\circ$ . For connection to take place, the IMF must be approximately antiparallel to the GMF (*i.e.* have a southward component) in the merging region. Recall that when connection takes place at one GMF pole, ionizing galactic cosmic ray flux decreases at that pole and increases at the unconnected pole producing an NSA in lightning but, possibly, almost a null effect on overall current to the electrosphere. Thus, NSA's in high latitude atmospheric ionization occur primarily when a southward IMF encounters the earth. In contrast, low latitude atmospheric ionization is constantly affected by all relative orientations of the IMF and by the field conditions many earth radii away from the magnetopause, especially so when the IMF is most homogeneous. Of course, the maximum increase in low latitude atmospheric ionization occurs when the IMF is antiparallel and the equatorial cosmic ray cutoff is lowest, admitting the largest number of galactic cosmic rays. Thus, an antiparallel orientation (southward IMF) decreases lightning incidence at the equator (due to EqM) and at one pole (due to NSA). Recall that, due to mirroring, the increase in ionizing flux at the unconnected pole is smaller, and hence associated effects are smaller than at the connected pole, preventing a "plus-minus symmetry" in the NSA. In contrast, a parallel orientation (northward IMF) decreases ionization at all latitudes resulting in a lightning increase at both poles and the equator.

Briefly, four angles of interest are (1) the  $7.25^\circ$  tilt of the sun's spin axis toward the earth's 7 September position placing the earth in northern heliographic latitudes from 6 June to 6 December, and southern from 6 December to 6 June; (2) the  $23.5^\circ$  tilt of the earth's spin axis directly toward the sun on 21 June, away on 21 December, forward along the direction of earth's orbital motion on 21 September, and backward on 21 March; (3) the mean direction of the IMF which is along a spiral arriving at earth  $45^\circ$  west of the earth-sun line; and (4) the  $12^\circ$  tilt of the GMF dipole from the earth's spin axis which will be ignored in this discussion of



seasonal (not hourly) orientation changes. On 21 December, when the GMF tilts away from the sun, the IMF would be most nearly parallel to the GMF in positive ("away") sectors if the azimuthal (spiral) component could be ignored. Similarly, on 21 March, when the GMF points backward along the orbit, positive sectors would be most nearly parallel if the radial component is ignored. In this vein, one expects maximum parallelism (due to turbulence about the average spiral field direction) to occur near **21 February** for positive sectors and maximum antiparallel conditions on the same date for negative (IMF toward the sun) sectors. On 21 August, the opposites should hold, i.e. maximum parallelism for negative sectors, etc. The principles of this and of the previous paragraph can be applied to estimate the relative probability of lightning incidence fluctuations at different times of year. **Clearly**, connection (i.e. antiparallel orientation) is favored for positive sectors in the fall and negative sectors in the spring. Thus, one expects strong lightning incidence fluctuations that correlate with IMF sector polarity at these times. Because geomagnetic noise is strongly influenced by connection [15], geomagnetic disturbance indices should exhibit the same fall positive and spring negative modulation. This, in fact, has been observed to hold for the C9 index in data spanning the interval from 1962 to 1975, somewhat more than one sunspot cycle [16].

The solar dipole reverses polarity during years of high sunspot number, approximately two to three years after the sunspot maximum, and retains the new polarity through the following minimum until the next post-maximum reversal [17]. During the present years of the 1986 solar minimum epoch, the southern half of the sun has a north magnetic pole. Thus, flux points out or "away" from the sun's southern hemisphere (as in positive sectors) and into or "toward" the northern half (as in negative sectors). However, in the simplest description, instead of pointing north in the equatorial plane like the GMF, the flux is dragged outward by the radially expanding highly conducting (collisionless) solar wind plasma so that the average direction of the IMF is approximately parallel to the equatorial plane pointing outward (along the spiral direction) just south of the plane and inward just north of the plane (the plane must therefore contain a current sheet). Because the earth is at south solar latitudes from 7 December to 7 June, it would be in a positive (outward flux) sector continuously for six months if the current sheet remained in the equatorial plane. However, in what is called the Rosenberg-Coleman effect, because of the so-called "baseball seam" shape of the source regions on the solar surface, the current sheet is warped, curving sinusoidally above and below the solar equatorial plane which it usually divides into four sectors. When the amplitude of warp is larger than  $7.25^\circ$ , the plane of the ecliptic is also (usually) divided into four sectors which rotate with the 27-day period of the sun. Frequently, low amplitude or asymmetry of warp result in only two IMF sectors [18]. Thus, approximately two to four times per month a sector boundary crosses the earth, placing it alternatively above or below the warped current sheet with corresponding changes in IMF polarity occurring within a few hours [19, p. 77; this reference is a compendium]. Because of the  $7.25^\circ$  tilt, the sectors are not of equal width, resulting in more time in the polarity determined by the heliographic latitude of earth when it is far from zero as in spring and fall. This result of current sheet warping combined with the heliographic latitude excursions of earth is called the Rosenberg-Coleman effect [20]. A number of annual and 11-year variations are predicted as direct results of the fact that even very small amplitude warps will move the current sheet across the earth when it is at 0° solar latitude, thereby maximizing the number of IMF sector boundary crossings in December and June. As examples, peaks are expected in December and June for both lightning frequency (as

indicated by suitable sferics) and geomagnetic disturbances. Also, many 22-year variations should result according to the magnetic coupling model when the geometrical factor dominance (of positive sectors in the fall and negative in the spring) is combined with the appropriate polarities by the solar magnetic dipole reversal. An example will be given in a later section discussing Stringfellow's lightning studies.

Solar wind speed is expected to influence magnetic coupling for several reasons, most of which are enhancing. As a first example, the rate of flux merging during connection is dependent upon the rate IMF is being transported into the merging region by the solar wind. Also, for a given IMF strength and solar wind particle density, the pressure increase due to higher solarwind speed would have at least two effects: (1) compression of the GMF with large inductive effects at earth, and (2) an increased susceptibility to connection because flux is removed from the compressed (high energy density) day side GMF by merging, consequently lowering the pressure. A third possible influence is an increasing homogeneity of the IMF we postulate may occur on the scale of about 10 GMF's (i.e. 100 earth radii) or so, even though the general trend is toward more turbulence on larger scales as solar wind increases. If this effect occurs, it would be apparent as a decrease in the IMF wavelength spectrum at frequencies of .001 Hz (and slightly below) near solar maximum when the spectral content of still lower frequencies is increasing (i.e. a steepening in spectral slope at the low wavelength end). The decrease of low frequency IMF homogeneity at solar maximum is thought to be due to magnetohydrodynamic effects (for a discussion of theory and measurements see reference 21). If the frequency spectrum in the .001 Hz interval rises less than the wind speed, the homogeneity in that scale range will increase. As solar maximum is approached, such an effect may explain the enhanced EqM and diminished NSA observed in NM data [6]. Decreased frequency of connection is expected because variation about the IMF mean position is needed to provide the close antiparallelism that favors merging. However, when connection does occur near solar maximum, the NSA effects should be larger because of the greater solar wind speed transporting the merging flux against the GMF and, possibly, the greater IMF amplitude and homogeneity. Thus, near solar maximum, NSA's may be less frequent but more intense. Such an effect has been reported in low pressure trough vorticity [19, p. 196].

At different latitudes on earth, responses may not be all similar for a given input (such as the changes in 10 km ionization produced by the NSA and EqM effects of magnetic coupling). This possibility, as well as the subtleties of the physics, should be considered in analysis by this model (or by other methods) of the vast array of diverse phenomena shown to correlate with solar activity [19]. An excellent example is the intensification of low pressure troughs forming in the Gulf of Alaska by IMF sector boundary passage, especially when IMF polarity changes from negative to positive. This effect exhibited high statistical correlation only in the winter. The magnetic coupling model explains both the high latitude and seasonal aspects as follows: (1) in positive sectors, connection of the north GMF pole to the sun reduces the 10 km ionization permitting cirrus formation to accelerate in that altitude region thus trapping heat in the system that would otherwise have been lost by radiation [13]; (2) the winter dominance is explained by the much greater prevention of cooling afforded by high cirrus when no insolation is present and the system must radiate to a 3°K cloudless sky if the (approximately 230°K) cirrus layer does not form; and (3) the approximate equality of sector lifetime and transit time of the system from a source region at high latitude exerts a form of resonant effect (in contrast to the low latitude situation discussed

below). Because EqM does affect upper air ionization at low latitudes, sector synchronous modulation of cirrus is expected there also. However, the broad longitudinal extent and the lower average wind speeds of equatorial source regions make air mass residence time much longer than IMF sector lifetimes and prevent the quick response and resonance effects of high latitude systems. Magnetic coupling effects, of course, are still expected to appear promptly in low latitude lightning incidence which is not slowed by a dependence on rate of heat loss. Now, the lesson of this paragraph can be expressed (regarding the subtlety of these relationships in general and of latitudinal effects in particular). In spite of the seeming cancellation of cirrus modulation having two or more alterations during low latitude air mass residence time, integrated second order effects may be significant because sector widths are systematically unequal especially in the spring and fall near the maximum heliographic latitude excursions of earth. For example, during this cycle 21 minimum epoch, the broadest IMF sectors in spring will be positive (the polarity of the sun's southern hemisphere) tending to decrease ionization and therefore increase cirrus [13] (and also, incidentally, lightning, sferics, Kp, etc.). In the fall, the widest sectors will be negative. In the even numbered cycles (i.e. 20, 22, etc.), these seasonal polarity dominances will be reversed. This particular example, being a Rosenberg-Coleman effect, will of course disappear near the solstices when the earth is crossing the sun's equator and sector widths become equal.

There are other processes such as solar flares and cosmic ray Forbush decreases that can have important effects on lightning incidence. Such effects can usually be deduced by simply remembering that changes in 10 km ionization and in lightning frequency are predicted to vary inversely.

**MAGNETIC COUPLING THEORY: APPLICATIONS**--In addition to the diverse examples discussed above, application of the magnetic coupling model to a few important unexplained findings related to lightning are presented in this section. The model suggests lack of a consistent theory has resulted in misinterpretations that in some cases have prevented integration of valid data considered conflicting and in others have generated misconceptions regarding which variables are causal and which simply covariant. The authors cited here are, in general, not the sources of the concepts suggested to be erroneous by this paper but are merely reviewing the literature.

Lightning Correlations: 11 and 22 Year--An extensive series of studies of lightning and electrical power line faults due to lightning in Britain has shown a remarkable correlation with sunspot number. Smoothed data for lightning observations as thunderstorm days by 40 weather stations were reported by Stringfellow to exhibit a positive correlation of 0.8 for approximately 40 years spanning four solar cycles (numbers 17 through 20) [22]. Two features of this study that are most apparent in Stringfellow's Figure 1 are of considerable significance to the solar-activity/ lightning-incidence question and will be considered here. These features are the 11-year correlation widely considered to be conflicting with other data, and the 22-year correlation which, to this author's knowledge, has not previously elicited extensive comment in the literature.

One of the principal reasons cited for considering the British data anomalous was the failure to detect a difference in lightning incidence due to the 11-year cycle in data from the 1965 solar minimum (OSO-2) and 1969 solar maximum (OSO-5) satellite experiments of Vorpahl, Sparrow and Ney [1]. Although those authors were well aware of the low latitude extent (within approximately 30° of the equator) of their data, the strong difference (a factor of 5 or greater depending upon altitude) in solar cycle modulation of upper atmosphere ionization between tropical and English latitudes definitively demonstrated by Ney [12] seems to have been ignored

by much of the community. However, because of this latitude difference there is no disagreement between these data sets according to the magnetic coupling model.

The 22-year correlation of Stringfellow's data is extremely interesting. The annual lightning index peaks for solar cycles 17 through 20 have the following characteristics: (1) they alternate in height with 17 and 19 about the same amplitude (within 4%) and average significantly higher (about 10%) than the average of peaks 18 and 20 which also are close together in height (within 3%); and (2) the lightning index peaks in each case slightly lead the sunspot peaks (by about one year). These characteristics are predicted by the magnetic coupling model as follows. Because the solar dipole field reverses 2 to 3 years after solar sunspot maximum [17; or 19, p. 79] and because the lightning peaks occurred slightly before the sunspot peaks, the solar polarity during each peak would be the same as in the preceding minimum which were positive, negative, positive, and negative, respectively (notice following the reversal during the 1980 maximum for cycle 21, our present solar dipole polarity is negative). Thus, for example, during most of the lightning peak years associated with the sunspot maximum 19, the northern half of the sun was a magnetic north pole (which favors positive sector connection from June to December) and the southern half was a magnetic south favoring connection in negative sectors to the south pole of earth. This should considerably enhance lightning incidence in Britain (northern latitudes) in "fall" (i.e. from June to December) and in southern latitudes in "spring" (i.e. from December to June). However, because of the weakness of NSA at the unconnected pole, the decreases in "spring" in England should be much less than the increases in "fall" providing a significant net enhancement for each such year in the rising portion of the odd numbered sunspot cycles. Conversely, in the even numbered sunspot cycles, the solar dipole is reversed and there is no "fall-positive"/"spring-negative" enhancement of connection.

Enhancement of 10 km Ionization, at Low Latitudes--As discussed earlier in the description of EqM, low latitude 10 km ionization is found to change very little over the solar cycle when a sufficient number of measurements are made and averaged together for each year. For example, the increases in 10 km ionization from solar maximum to solar minimum at the equator and at 55° (north or south) geomagnetic latitudes are approximately 3% and 18%, respectively; at 30 km for the same latitudes the increases are 4% and 100%, respectively [12]. Thus, the finding of large increases in ionization lasting for a day or so at low latitude by a number of investigators was surprising. Sellars summarized these and included the remarks by W. O. Roberts regarding the importance of this anomaly and the need to explain it [23, p. 66]. As shown in this paper, EqM's of about 30% at the top of the equatorial atmosphere are explained and predicted by the magnetic coupling model and have been observed by satellite [6].

Modulation of the Electrosphere Potential--The increases and decreases in both the electrospheric potential and the fair weather electric field associated with increases and decreases in 10 km ionization have been clearly defined by Markson and others for over a decade. However, several reviewers have commented on the almost prevailing supposition that (1) the enhanced potential and its gradient "somehow produce increased lightning" [23, p. 65], and (2) "solar effects on terrestrial meteorology occur through modulation of the global fair-weather electric field" [23, p. 75]. The magnetic coupling model shows clearly that changes in lightning and in the subject potential and its gradient occur as results of alterations in upper air ionization because of the latter's influence on the division of thunderstorm generator current between leakage and charging. Thus, changes in the field quantities are predicted to be co-results, not causes of major

lightning alterations. Even in weather alteration as suggested in discussion of the cirrus mechanism below, the field quantities are predicted by the magnetic coupling model mechanisms described in this paper to exert only secondary effects.

The Cirrus Mechanism--The magnetic coupling model suggests the rate of cirrus formation is inversely influenced by 10 km ionization as follows. Any process producing enhanced 10 km ionization increases charging of water molecular aggregates because of their high capture cross-section (via inelastic collisions) decreasing recombination of the ions. The charged aggregates are then transported out of the thin cirrus region by the 5 volt/m field (before they can grow to micron size) impeding cirrus formation and enhancing cooling of the surface below [13]. As pointed out by one investigator, the common supposition is exactly the reverse of this: "Most people think" extra ionization increases nucleation and thin cirrus [24, p. 133]. Notice, in the first scenario above, the rate water molecular aggregates are transported out of the region is proportional to both the ionization and the field strength. However, the field strength variations are much less important than the ion density variations for two reasons related to amplitude and phase. Before these are briefly discussed, it is appropriate to recall the converse mechanism predicted by the model (in which positive sector connection decreases northern latitude 10 km ionization enhancing cirrus formation and retarding heat loss from the system). This sequence is expected to be most important in sun-weather relationships. "Local" changes in tropopause ionization amplitude of approximately 30 to 100% can occur in polar regions quickly and even on a weekly basis due to IMF connection NSA's, Forbush decreases, and solar flares. Again, "local" effects such as NSA's are expected to produce only small field changes. Because of the high conductivity of the electrosphere, to obtain a 30% change in the field amplitudes, some global effect such as daily rotation through the 1800 UT thunderstorm maximum, or the modulation of cosmic ray intensity by solar activity over a sunspot cycle would be needed. Even though global effects can be impulsive as in Forbush decreases, the phases are opposite or mixed in such events: i.e. the decrease in cosmic ray ionization both diminishes the thunderstorm leakage current, opposing an increase in electrosphere potential, and decreases the clear air conductivity, slowing the fall in electrospheric potential. Anomalous situations occur in which 10 km ionization decreases and higher altitude ionization increases for obvious reasons. Although Reiter and others have shown large changes in field quantities do occur in major impulsive events, such events are much less frequent than the IMF sector effects and usually are additive to the latter. For a review of the literature and numerous considerations involved see reference 19.

Cosmic Rays and Lightning Frequency--The IMF sector synchronous modulations of cosmic rays and mechanisms to explain their involvement in atmospheric process have received attention since 1969 [6, 25]. The studies of Lethbridge [26] have shown a strong statistical correlation between cosmic ray intensity fluctuations and "thunderstorms" (lightning). Those studies found a maximum in lightning incidence approximately 3 days after the cosmic ray intensity fluctuation maximum. This finding has since been interpreted to indicate a causal relationship between the lightning maximum and the preceding cosmic ray maximum. However, most such cosmic ray maxima are related to IMF sector boundary passage. When a maximum precedes the boundary, a strong cosmic ray minimum follows it. This minimum would be in essentially exact coincidence with the lightning maximum. The magnetic coupling model explanation of lightning increases due to ionization decreases has been discussed elsewhere in this paper. That model suggests, therefore, that the demonstrated correlation described above is real, but that the cosmic ray decrease causes the lightning maximum.



Runaway Electrons--Theoretical and experimental support has in recent years reawakened interest in the suggestion made 60 years ago by Wilson that, in the high field regions of **thunderstorms**, electrons might gain more energy than lost in **collisions** and radiation and hence accelerate for considerable distances. Kasemir **has** shown theoretically that sufficiently strong fields may in fact exist in association with lightning stroke "tips" [27]. Parks et al. detected x-ray bremsstrahlung of the expected character above **thunderstorms** [28]. **It** has been interpreted that such radiation increasing ionization above thunderstorms may be a regenerative process. However, as has been shown in this paper, the magnetic **coupling** model predicts increases in ionization above thunderstorms result in a decreased charging rate and less lightning. Hence, although the existence of runaway electrons seems **reasonably** established, the theory presented here suggests **it** is a self-limiting and hence, possibly, a rare occurrence rather than a common regenerative aspect of the storm.

Southward IMF and the Auroral Oval--The process of connection is enhanced by a southward **IMF**. Such merging erodes day-side IMF and has been predicted to increase flux coupled through the earth, enlarging the auroral oval. A strong correlation between size of the oval and southward field has in fact been shown by Holzworth et al. [29].

## SUMMARY AND CONCLUSIONS

By means of a small number of mechanisms, the magnetic coupling model provides a self-consistent set of explanations that unify a large number of observations reported to correlate with solar activity. The successful application of this model and its mechanisms to the physical processes included as examples in this paper leads to the conclusions that:

- The magnetic coupling model may be one of the principal links between solar activity and atmospheric processes affecting weather, climate and lightning.
- The magnetic coupling model exerts its control over atmospheric and other processes primarily by modulation of the galactic cosmic radiation via **IMF-GMF interactions**.
- The cosmic ray variations exert their effects, in turn, by modulating the level of ionization from the upper troposphere through the tropopause.
- A wide variety of previously unexplained phenomena reported to correlate with solar activity appear tractable to analysis. This applies especially to processes of interest in weather, climate and atmospheric electricity.
- The electrospheric potential and fair weather electric field are also modulated by the cosmic ray/atmospheric ionization link. The variations in these field quantities are predicted to be only of secondary importance in comparison to the variation of ionization as mediators of solar-terrestrial effects.
- Investigation of solar-terrestrial effects is greatly simplified if, in fact, that more easily measured 10 km ionization rate proves to be the principal independent **variable** with **the** atmosphere.

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16. ABSTRACT  A theoretical model is described that unifies the complex influence of several factors on spatial and temporal variation of lightning incidence. These factors include the cosmic radiation, solar activity, and coupling between geomagnetic and interplanetary (solar wind) magnetic fields. Atmospheric electrical conductivity in the 10 km region is shown to be the crucial parameter altered by these factors. The theory reconciles several large-scale studies of lightning incidence previously misinterpreted or considered contradictory. The model predicts additional strong effects on variations in lightning incidence but, possibly, only small effects on the morphology and rate of thunderstorm development.					
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